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W-1 SODIUM LOOP SAFETY FACILITY
EXPERIMENT CENTERLINE FUEL
THERMOCOUPLE PERFORMANCE

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W-1 SODIUM LOOP SAFETY FACILITY EXPERIMENT CENTERLINE FUEL THERMOCOUPLE PERFORMANCE

1.0 INTRODUCTION

The W-1 Sodium Loop Safety Facility (SLSF) experiment is the fifth in a series of experiments sponsored by the Department of Energy (DOE) as part of the National Fast Breeder Reactor (FBR) Safety Assurance Program. The experiments are being conducted under the direction of Argonne National Laboratory (ANL) and Hanford Engineering Development Laboratory (HEDL). It was the first in the series of HEDL SLSF experiments and was conducted in cooperation with the Advanced Reactor Systems Division of General Electric Company (GE/ARSD). The test facility, located in the Engineering Test Reactor (ETR) at the Idaho National Laboratory (INEL), is operated by EG&G Idaho, Inc.

The irradiation phase of the W-1 SLSF experiment was conducted between May 27 and July 20, 1979, and terminated with incipient fuel pin cladding failure during the final boiling transient. Experimental hardware and facility performed as designed, allowing completion of all planned tests and test objectives. This paper focuses on high temperature in-fuel thermocouples and discusses their development, fabrication, and performance in the W-1 experiment.

2.0 GENERAL EXPERIMENT OBJECTIVES AND DESCRIPTION

2.1 EXPERIMENT OBJECTIVES

The W-1 experiment has two distinct and separate objectives. The primary objective is to evaluate fuel pin heat release characteristics during loss-of-piping integrity (LOPI) accident flow and power conditions. Clinch River Breeder Reactor (CRBR) conditions during this accident are being used as representative of FBR's. A sequence of four LOPI transients were to be conducted to collect data at the different fuel pin conditions of:

- fresh, unrestructured fuel,
- fresh, restructured fuel,
- irradiated, uncracked fuel (after steady-state irradiation), and
- irradiated, cracked fuel (after shutdown and startup).

The second objective of the W-1 experiment is to determine stable sodium boiling and recovery limits (boiling window) as a function of fuel pin power and bundle flow rates. These boiling tests will culminate with incipient fuel pin failure to determine the range of power/flow ratios over which stable sodium boiling exists. Experimental objectives are summarized in Table 1.

TABLE 1

HEDL W-1 SLSF EXPERIMENT OBJECTIVES

- Resolve Breeder Reactor safety issues of:
  - -- Fuel pin heat release characteristics during LOPI accident conditions
  - -- Sodium boiling and void development characteristics
  - -- Coolant boiling conditions required to produce incipient fuel pin failure

These objectives are consistent with resolution of major second level FBR safety assurance (LOA-2) issues identified in the Fuel Pin Failure Mechanisms Program Plan.[1] They will provide increased insight and understanding of phenomena that inherently terminate hypothesized accidents with only limited core damage. Furthermore, the boiling window data will expand sodium boiling data already obtained in the Thermal-Hydraulic Out-of-Reactor Safety (THORS) Facility at Oak Ridge National Laboratory.

2.2 EXPERIMENT DESCRIPTION

The SLSF in-pile loop, located in the Engineering Test Reactor (Figure 1), is a doubly-contained closed sodium loop test vehicle 8.23 m (27 ft) long and weighing approximately 3400 kg (7500 lbm). The loop consists of a primary and secondary containment vessel, an annular linear induction electromagnetic pump (ALIP), a tube-and-shell, sodium-to-helium heat exchanger (HX), a 0.1 cm (40 mil) thick cadmium thermal neutron filter, loop sensors, removable top closure (RTC), and the instrumented test train (Figures 2 and 3).

During loop operation, 661^{o}K (730^{o}F) sodium flows through the downcomer region (between the test train and primary tube) to the bottom of the loop where the flow reverses direction and is split into the bundle flow at 1.95 kg/sec (4.29 lbm/sec) and by-pass flow at 3.98 kg/sec (8.77 lbm/sec). See Figures 4 and 5. The flow rises through the fuel bundle and by-pass regions of the test train and recombines above the outlet flow sensor. The sodium, now 755^{o}K (900^{o}F), passes through the remainder of the test train to the top plenum region, reverses direction, flows downward through the HX and ALIP, and returns to the downcomer annulus.

The heart of the W-1 loop is the instrumented test train. It is approximately 7.9 m (26 ft) long and contains 19 FTR size fuel pins with CRBR type axial blankets in a hexagonal bundle array. The test train contains 76 thermocouples, 16 pressure transducers, and four sodium flowmeters. In addition, the center seven fuel pins contain annular fuel pellets over the length of the active section and in-fuel thermocouples placed in the pins to measure fuel temperatures at three different elevations. The outer 12 pins

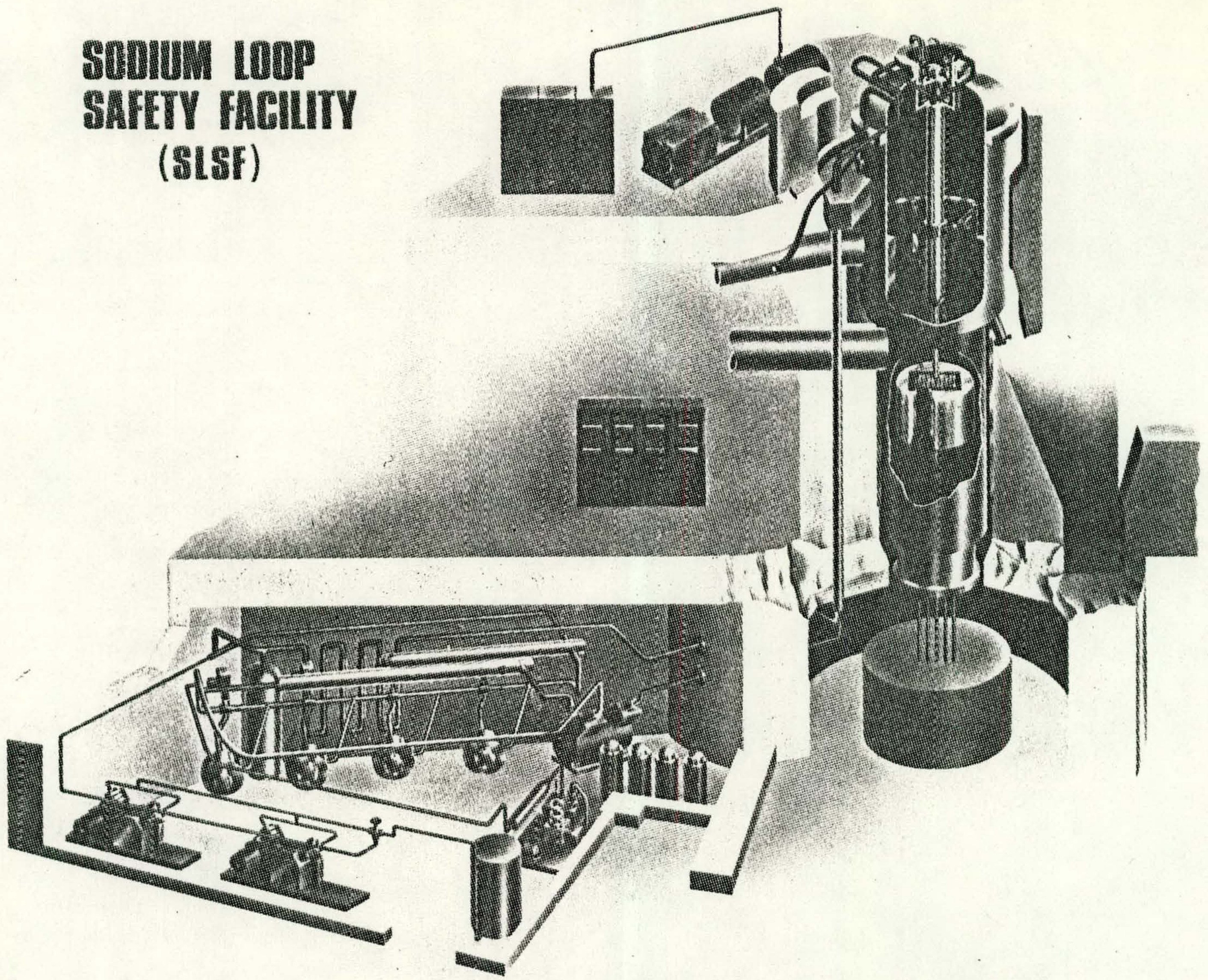

FIGURE 1. Sodium Loop Safety Facility (SLSF).

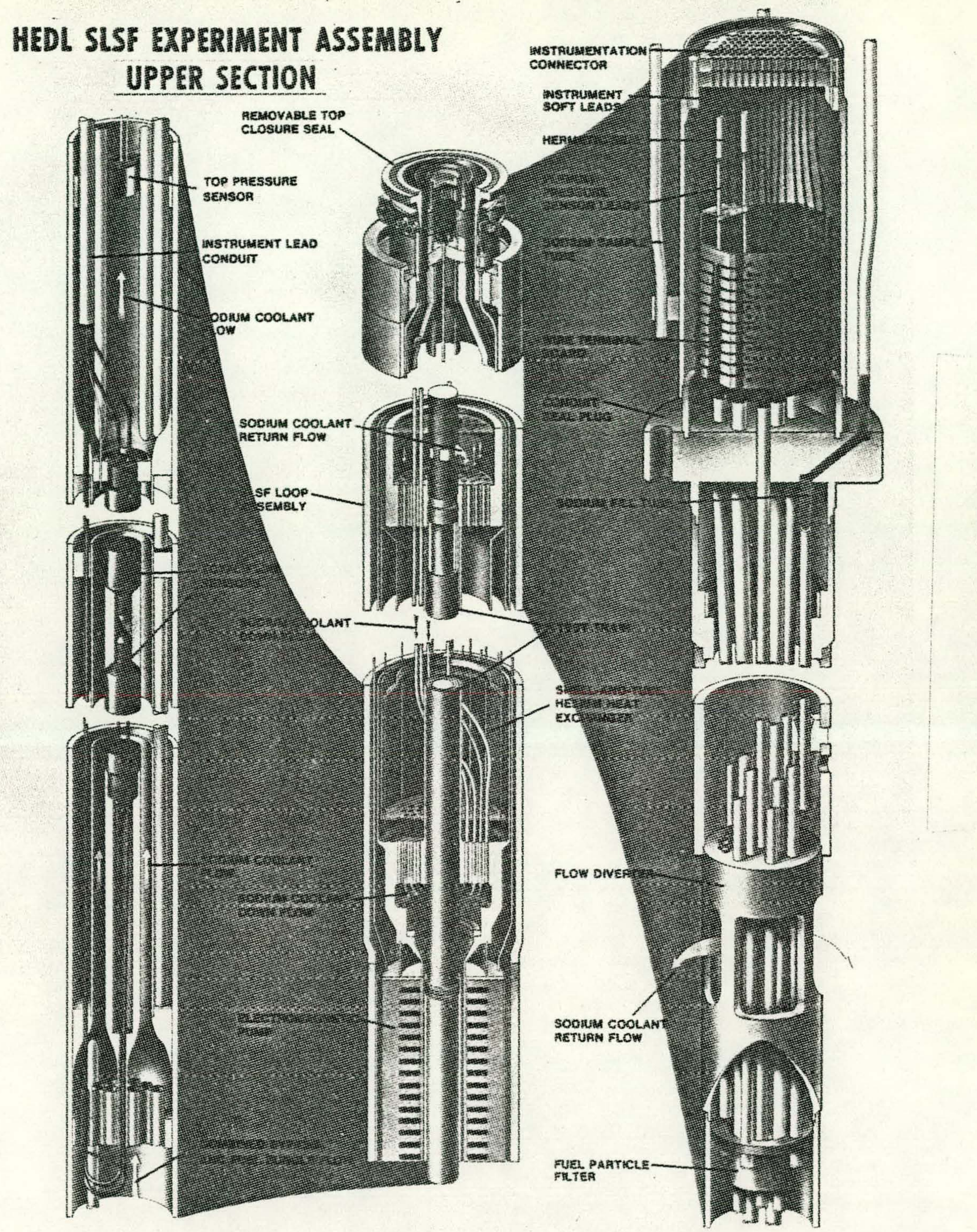

FIGURE 2. HEDL SLSF Experiment Assembly Upper Section.

HEDL SLSF EXPERIMENT ASSEMBLY

LOWER SECTION

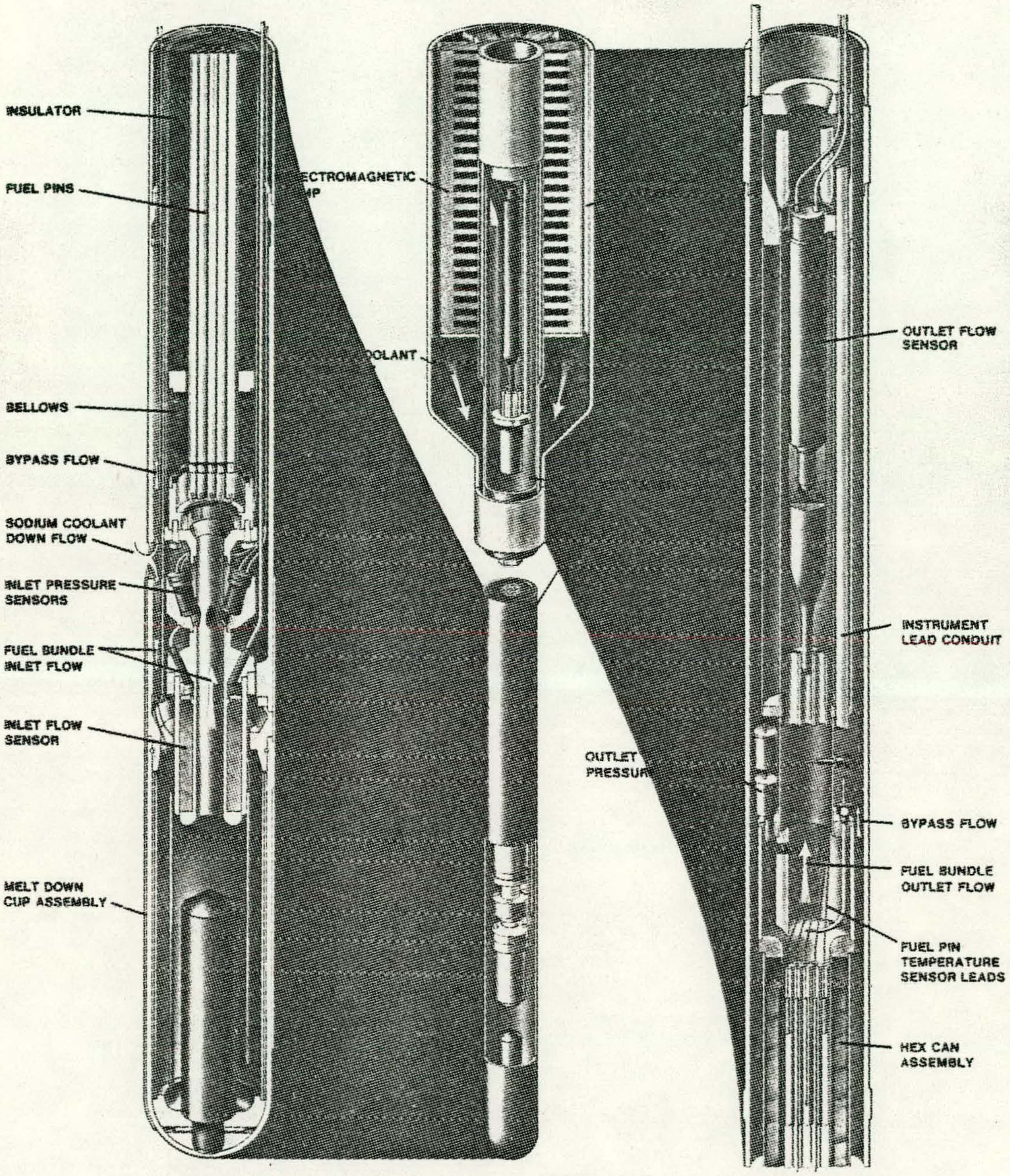

FIGURE 3. HEDL SLSF Experiment Assembly Lower Section.

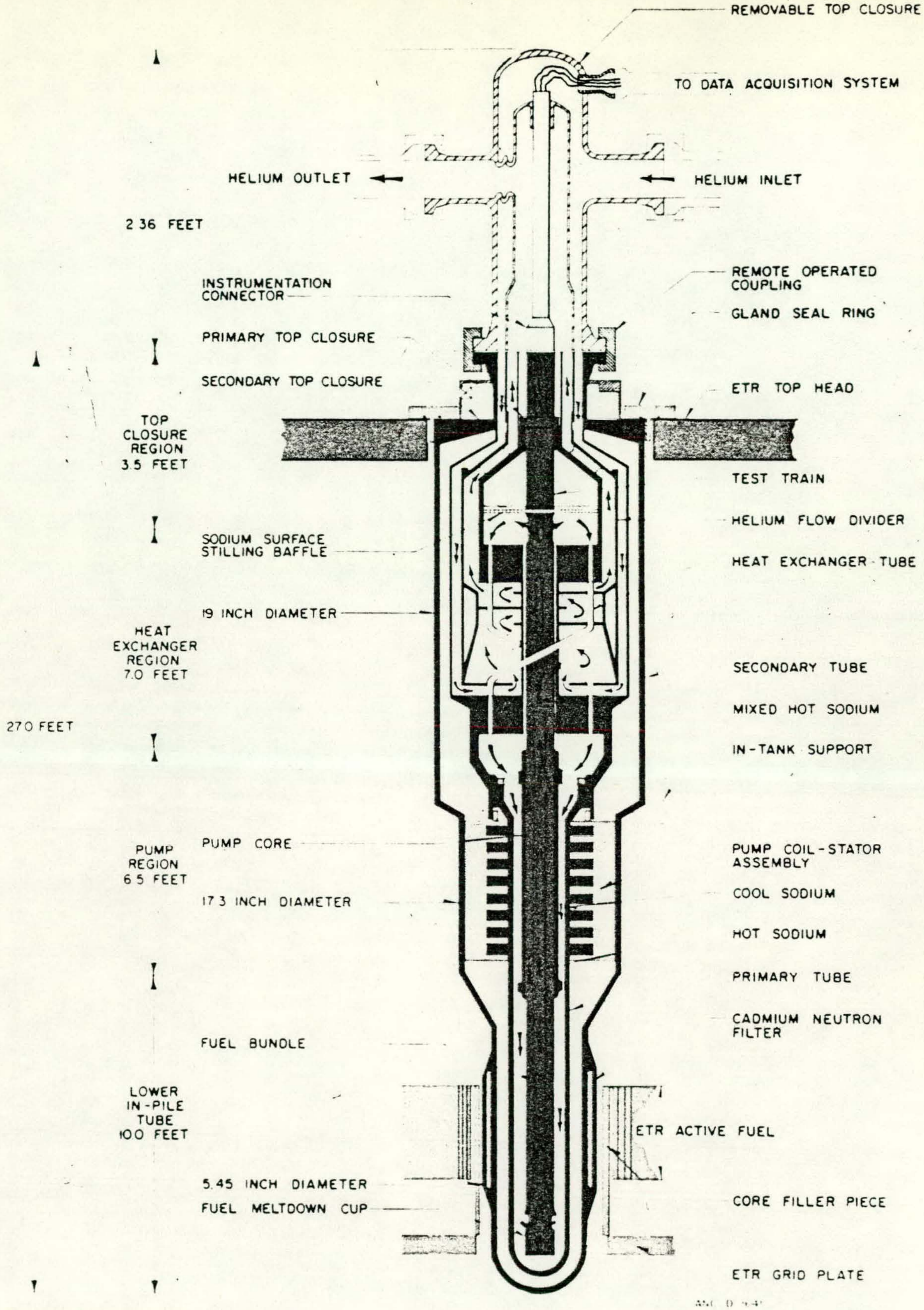

FIGURE 4. SLSF In-Pile Loop Cross Section.

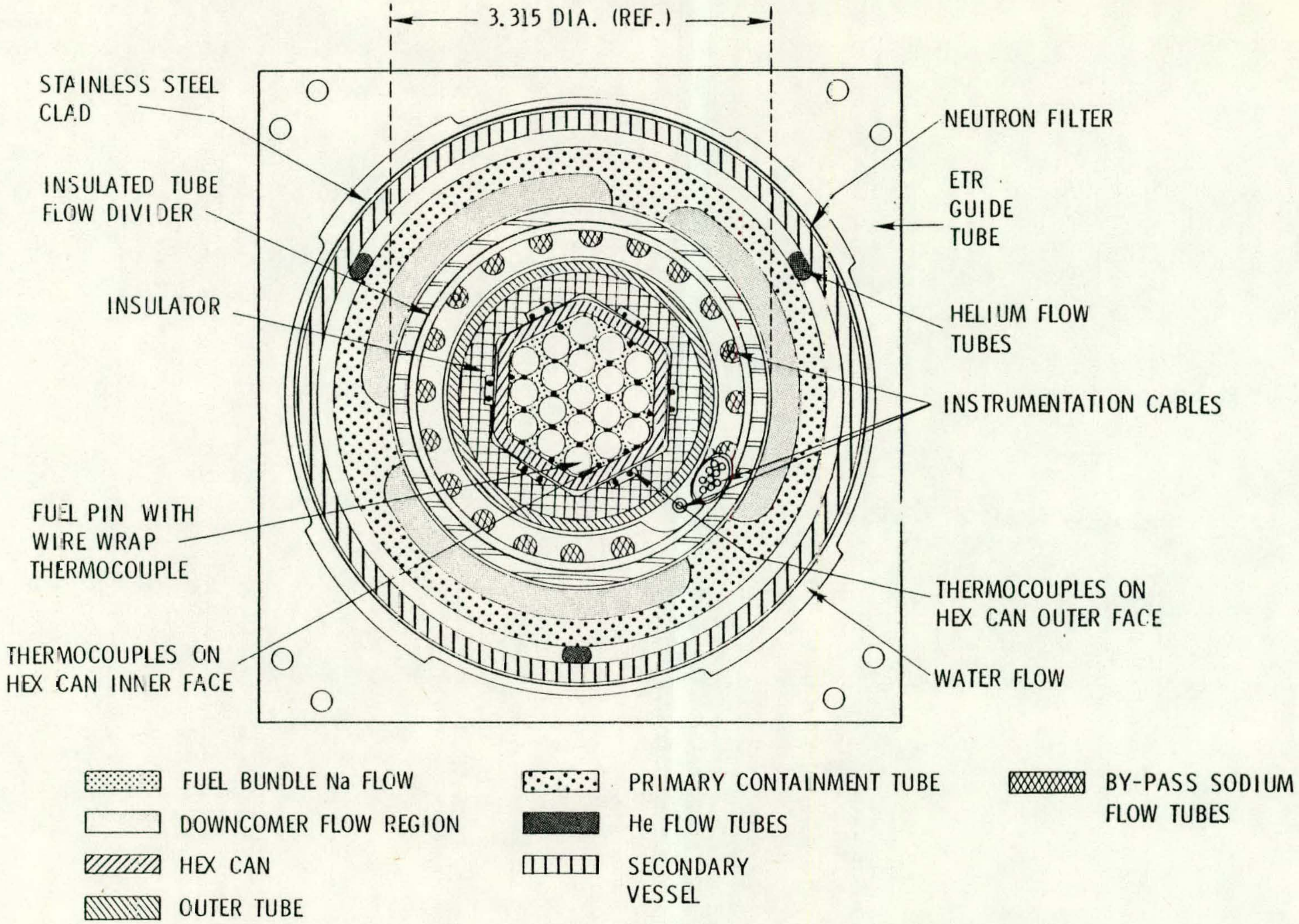

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FIGURE 5. Cross-Section of the W-1 SLSF in the Lower Test Section Region.

contain solid pellets (Figure 6). Fuel enrichments were selected to produce a flat power profile. Table 2 lists instrumentation utilized in the experiment.

3.0 IN-FUEL THERMOCOUPLE DEVELOPMENT AND DESIGN

3.1 IN-FUEL THERMOCOUPLE DESIGN REQUIREMENTS

Fuel centerline temperature data is vital to achieve the objectives of monitoring fuel behavior. To these ends, it was determined that the inner seven fuel pins be equipped with high temperature thermocouples located at various levels of the annlaar fuel column.

Extremely demanding requirements were imposed on in-fuel thermocouples due to the demanding environment created in the center of the fuel pins during the experiment. The thermocouples must function at temperatures of up to $2873^{o}K$ in a mixed oxide nuclear fuel. Error in accuracy must not exceed 2 percent over a minimum lifetime of 500 hours. Also, the dimensional restrictions are severe. The portion of the thermocouple which is inserted into the fuel column must not exceed 1.64 mm in diameter and must penetrate the fuel and insulator column to depths of 76.2 cm. Any transition to a base metal lead-in wire must occur in the fission gas plenum with a diametral restriction of 4.32 mm. Finally, units must provide a hermetic barrier against leakage of fission gas from a failed thermocouple sheath through the lead-in cable. Table 3 summarizes the requirements.

Schedule requirements dictated that the thermocouples be fabricated, tested, and delivered to the fuel pin fabrication facility within nine months.

3.2 IN-FUEL THERMOCOUPLE MATERIAL AND DESIGN DESCRIPTION

An in-depth literature search on high temperature thermocouples and thermometry and high temperature materials was conducted to determine the state-of-the-art in high temperature thermometry. From this research it was determined that the SLSF W-1 experiment would be best served by using

SLSF INSTRUMENTED PINS

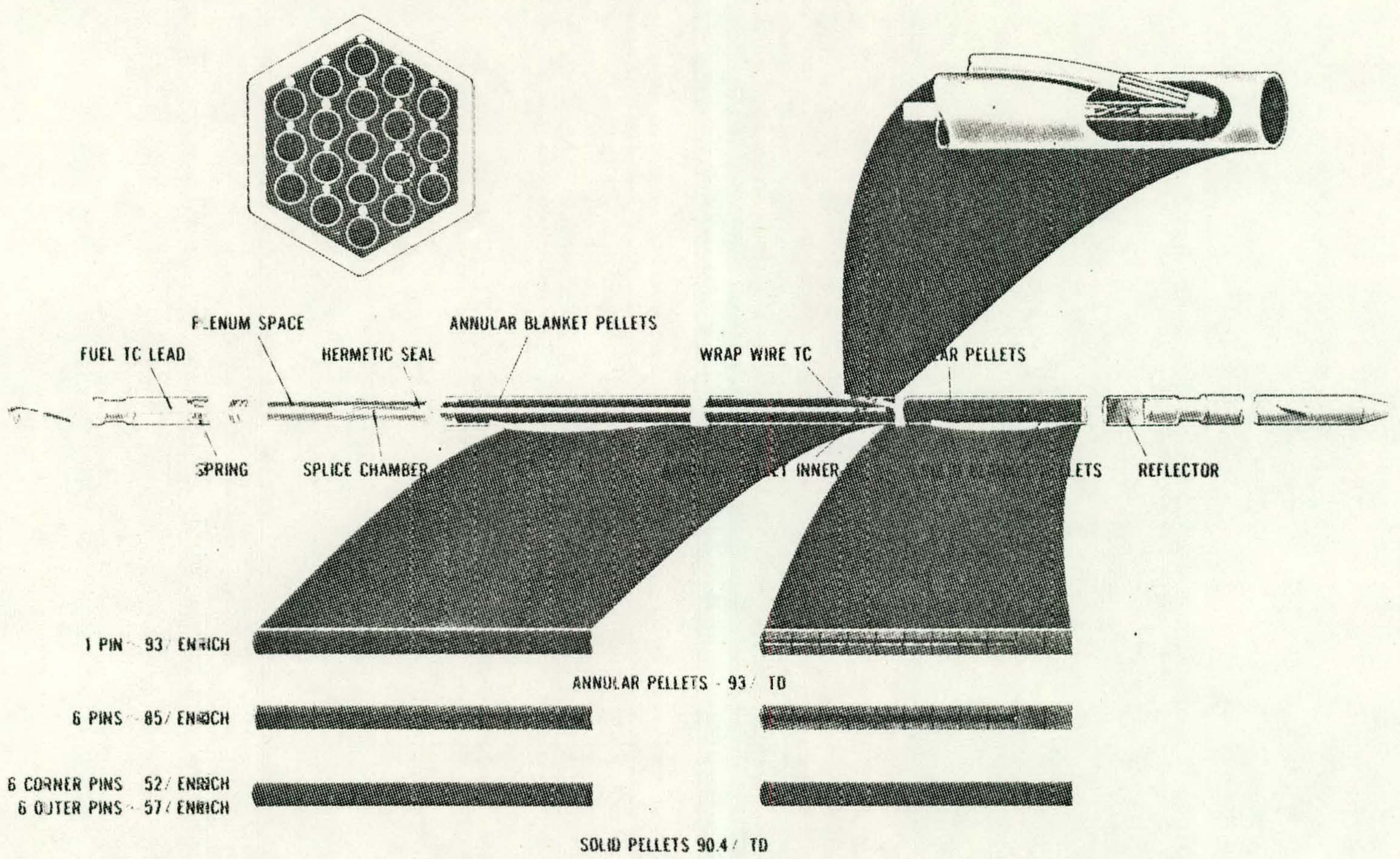

FIGURE 6. SLSF Instrumented Pins.

TABLE 2

HEDL W-1 TEST TRAIN INSTRUMENTATION

Variable	Instrument Type	Maximum Range	Number
Coolant Temperature	Chromel-P vs. Alumel thermocouple	2200°F (1477°K)	76
Fuel Temperature	W3% Re/W25% Re	4200°F (2589°K)	7
Bundle Inlet Coolant Flow	Permanent Magnet Flow Sensor	65 gpm (4.19 l/s)	1
Bundle Outlet Coolant Flow	Eddy Current Flow Sensor	65 gpm (4.19 l/s)	1
Total Coolant Flow	Eddy Current Flow Sensor	130 gpm (8.38 l/s)	2
Static Coolant Pressure	Strain Gauge Pressure Transducer	200 psi ($1.38 \times 10^6 N/m^2$)	6
	Eddy Current Pressure Transducer	100 psi ($6.89 \times 10^5 N/m^2$)	4
Dynamic Coolant Pressure	Strain Gauge Pressure Transducer	2000 psi ($1.38 \times 10^7 N/m^2$)	6

TABLE 3

SLSF W-1 EXPERIMENT IN-FUEL THERMOCOUPLE REQUIREMENTS

Measurement Performance Requirements:

Temperature Ranges:	1100 to 2873°K and 1100 to 2573°K
Accuracy:	± 2% of reading
Resolution:	5°K
Response Time:	1.0 second
Lifetime:	500 hours

Environment Requirements:

Temperature:	2873°K
Pressure:	$2.76 \times 10^6 N/m^2$ (400 psia)
Media:	Pu (UO_2) fuel, helium, fission products

Dimensional/Mechanical Requirements:

Sheath Diameter:	< 1.65 mm (0.065 inch)
Minimum Sheath Length:	0.58 m (23 inches) and 0.737 m (29 inches)
Transition Juncton Diameter:	4.32 mm (0.170 inch)
Compensating Cable Dimensions:	< 2.45 mm (0.096 inch) x 6.0 m (20 feet) long
Hermeticity:	Unit must contain fission gases in probe and cable.

in-fuel thermocouples, Types I and II. A Type I unit would be useful to temperatures of $2873^{o}K$, but would employ non-commercial, developmental materials. A Type II unit would use commercially available materials, but would be useful only to $2273^{o}K$ for extended times. Thermocouple materials and design specifications are listed for both the Types I and II units in Table 4.

The Type I in-fuel thermocouple makes use of a highly compatible combination of materials. The tungsten 3% rhenium (W3%Re) and tungsten 25% rhenium (W25%Re) thermoelements, insulators (hafnia), and sheath tubing (pure rhenium or tungsten 22% rhenium) are an exceptionally good material combination at temperatures above $2473^{o}K$.[2,3,4] Recent research on high temperature thermometry indicated that these combinations of materials are very stable at $2473^{o}K$ and that the sheath materials are very compatible with uranium oxide.[5] Compatability of the sheath material with $Pu(UO_2)$ also appears to be acceptable.[6]

The Type II thermocouple utilizes different materials in the probe section. The more commercially available beryllia insulators and molybdenum-50% rhenium alloy sheath tubing are used with W3%Re versus W25%Re thermoelements. The combination is quite reactive at $2473^{o}K$, but is reasonably stable at $2273^{o}K$. The sheath-thermoelement insulator subassembly is procured from a thermocouple vendor; the transition sleeve and hermetic termination are attached by HEDL.

Both the Type I and Type II thermocouples are transition type thermocouples. A refractory material probe is used in the high temperature in-fuel portion of the thermocouple. As previously described, the thermoelements are tungsten-rhenium alloys, insulated with refractory oxides and encased in a refractory metal sheath. The junction between the dissimilar thermoelements is a mechanically robust twisted and bead welded junction. This junction is insulated from the sheath as opposed to grounded to allow for differential expansion between the sheath, thermoelements and insulators.

TABLE 4

SLSF W-1 EXPERIMENT THERMOCOUPLE MATERIAL AND DESIGN SPECIFICATIONS

Thermocouple	Type I	Type II
Range	1100 to 2873°K	1100 to 2573°K
Accuracy	2% of reading	2% of reading
Resolution	5°K	5°K
Lifetime	500 hours	500 hours
Response Time	1 - 3 seconds	1 - 3 seconds
Insulation	Vitrified Hafnia	Vitrified Beryllia
Sheath	Rhenium, 1.6 mm (0.0625 inch) diameter	Molybdenum 50% Rhenium or Tungsten 22% Rhenium (W22%Re) 1.61 mm diameter
Compensating Cable	Allumel versus 308 SST, compacted MgO insulation, 304 SST sheath 2.4 mm (0.093 inch) diameter	
Configuration	Insulated junction, sheathed, transition thermocouple	
Thermoelements	W3%Re versus W25%Re, 0.254 mm (0.010 inch) diameter	

The probe section of the thermocouple is terminated with a small diameter hermetic seal. The termination serves a dual purpose of halting the leakage of fission gases through the thermocouple should the sheath crack and isolating the probe from possible contaminants in the cable and transition splice. Figure 7 shows a conceptual design drawing of the probe section.

The tungsten-rhenium probe section is joined to a compensating cable through a transition junction. Alumel and 308 stainless steel are useful compensating alloys with the W3Re versus W25Re up to temperatures in the fission gas plenum of up to $1073^{o}K$. The junction is insulated with split alumina insulators and sealed with a stainless steel tube. The design drawing for the transition junction and overall in-fuel thermocouple is presented in Figure 8.

4.0 FABRICATION OF THERMOCOUPLES

4.1 FABRICATION PHILOSOPHY

It is absolutely necessary to minimize miniscule level of contamination inside the thermocouple sheath. Any oxidizing agent corrodes the thermoelement at high temperature. Carbon, silicon, and metal contaminants diffuse into the thermoelements altering the calibration. Any metallic or carbon impurities in the insulators will cause them to break down electrically at high temperature and introduce shorting errors. Consequently, it was decided to subject all materials used in the thermocouple to rigorous procurement and material processing operations to insure the purity of the items. Furthermore, the probe was entirely assembled in an inert atmosphere glovebox and hermetically sealed before removal. Total themocouple assembly was conducted in clean room facilities with a final evacuation and backfill with high purity argon.

4.2 FACILITIES

A number of special purpose facilities at HEDL were used in enforcing the fabrication philosophy for the high temperature thermocouples. Table 5

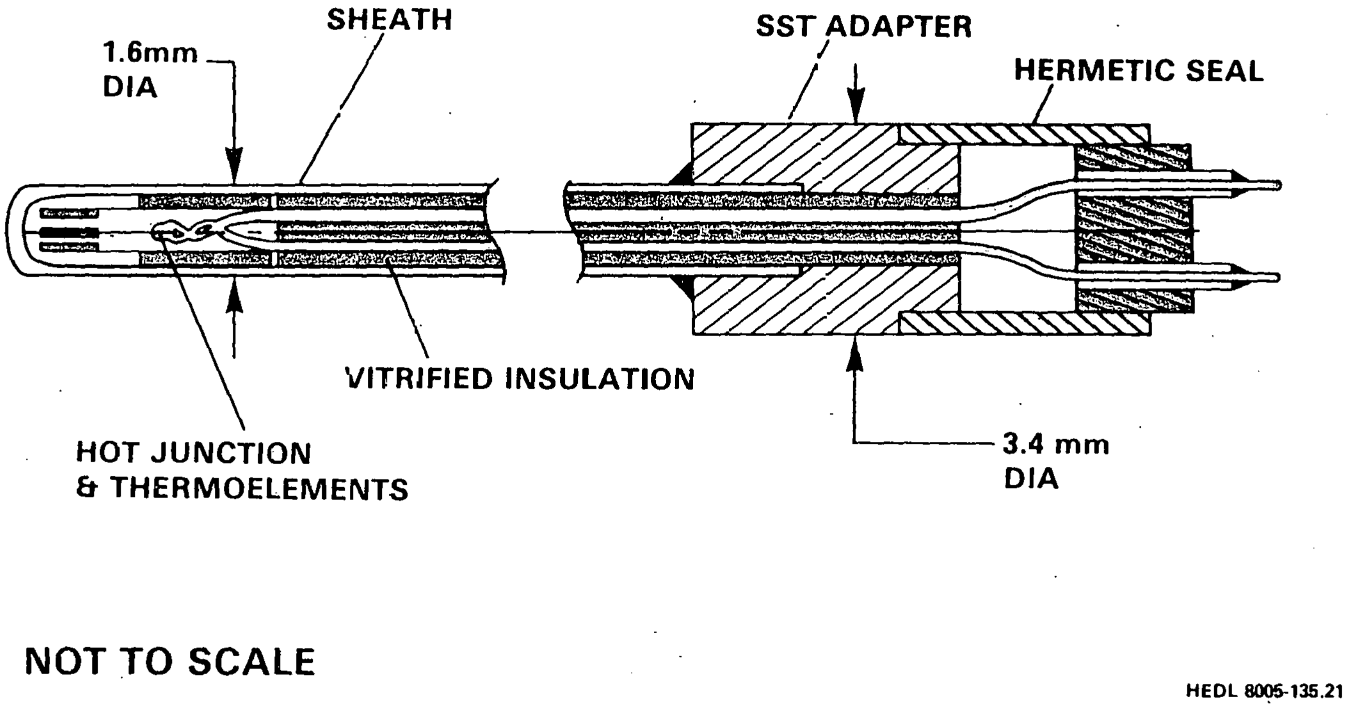

FIGURE 7. In-Fuel Thermocouple Probe Design.

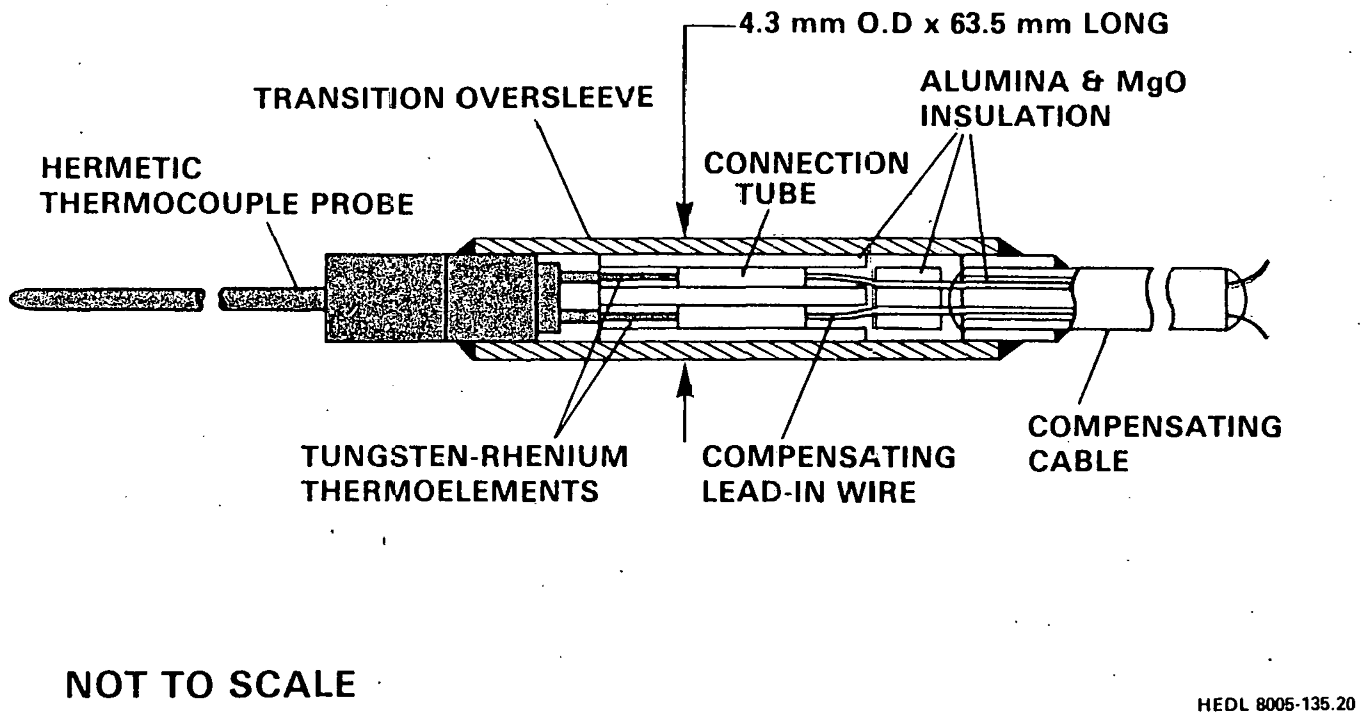

FIGURE 8. In-Fuel Thermocouple Design: Transition Junction.

TABLE 5

FACILITIES UTILIZED FOR IN-FUEL THERMOCOUPLE FABRICATION

- Vacuum/inert atmosphere fabrication glovebox with gas purification system.
- Adjoining 3273°K vacuum furnace.
- Automatic GTAW (Astro-arc) tube welding head for use in glovebox.
- Low amperage GTAW welding equipment in glovebox.
- Electron cloud brazing fixtures and power supply.
- Pulsed beam welder.
- Electron beam welder.
- Helium leak detection equipment for use both in and out of glovebox.
- Forty foot long vacuum tube furnace (800°K).
- Acid etching and ultrasonic solvent cleaning bench.
- General fabrication laboratory facilities.

lists general and special purpose facilities employed in the fabrication effort.

The vacuum/inert atmosphere glovebox was used extensively in processing the thermocouple components and assemblying the probe and overall thermocouple assembly (see Figures 9 and 10). Several of the important features of the glovebox are listed below:

- Large work area (0.8 m diameter by 2.5 meter long with four sets of gloves and an airlock.
- A recirculating gas purification system for inert gas or nitrogen which maintains the oxygen/water vapor content at less than 0.01 ppm.
- Evacuation capabilities to 2 x 10^{-4} torr in 20 minutes.
- Welding feedthroughs.
- Instrumentation feedthroughs.
- Leak testing feedthroughs.
- Access to a high temperature furnace though a flange in the bottom of the chamber. (See Figure 10).

The high temperature furnace was used extensively in processing the insulators and testing the thermocouples. It has the following features:

- Flange access with multiple fittings to the glovebox.
- An independent vacuum system with evacuation capabilities to 10^{-5} torr in 15 minutes.
- Heat zone dimensions of 0.66 m x 0.0635 m in diameter.
- Maximum furnace temperatures of 3273^{o}K (vacuum), 2673^{o}K (inert gas) or 2473^{o}K (hydrogen).
- Temperature monitoring with bare wire tungsten-rhenium thermocouples and a two color automatic optical pyrometer.

The circumferential weld of the transition sleeve to the hermetic seal would not have been possible without the programmable orbital GTA tube welding

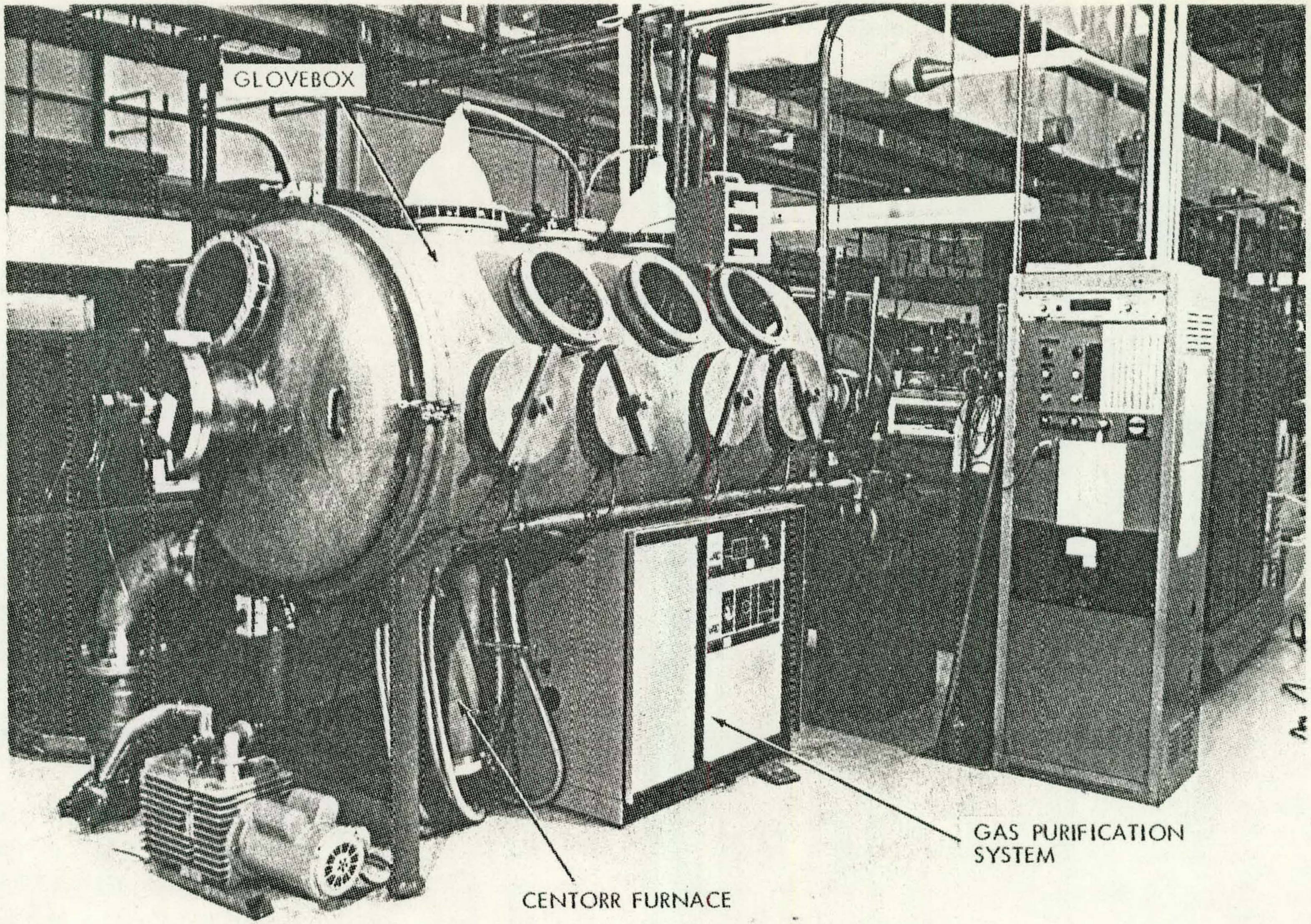

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FIGURE 9. Glovebox and Centorr Furnace Facility.

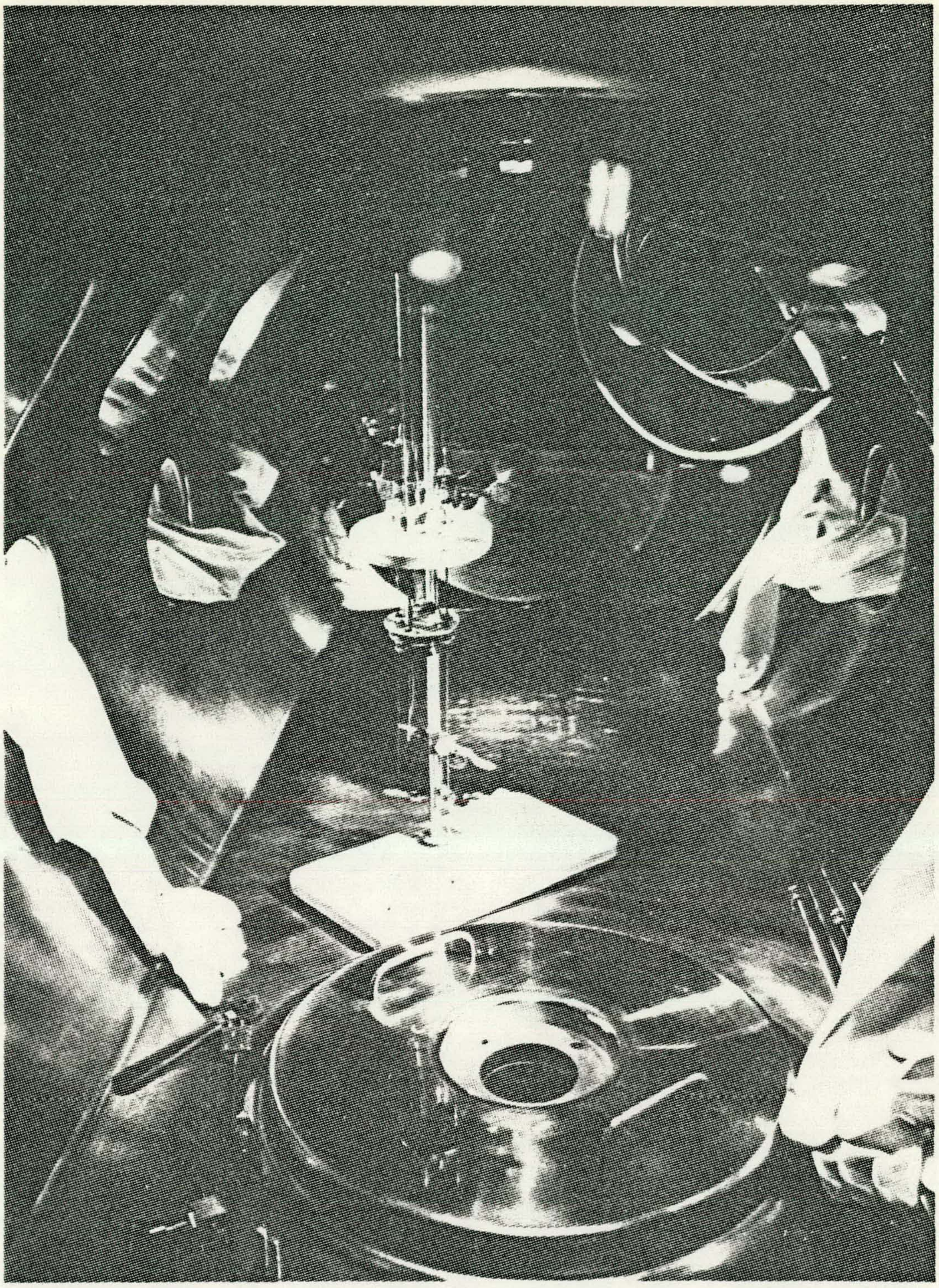

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FIGURE 10. Removal of Thermocouple From Furnace Calibration Facility for SLSF W-1 In-Fuel Thermocouples.

fixture and power supply. The device is shown in Figure 11 with the technician setting up the hermetic seal weld in the glovebox on a Type I probe.

Another critical joint is the refractory metal probe sheath to the transition sleeve braze. This step is accomplished using an electron cloud (emission) technique. A tungsten filament is placed around the joint, the glovebox is evacuated and 600 volts are imposed between filament and work piece (Figure 12). The filament is electrically heated to a temperature at which electron emission occurs ($\simeq 2473^{\circ}K$). The emission current is monitored with an amp meter and the copper braze ring observed visually through a telescope. The process is terminated when the braze flows and wets the components (Figure 13).

4.3 FABRICATION SEQUENCE

Table 6 shows the fabrication sequence for the thermocouple probe. All materials are thoroughly cleaned. Special attention is paid to the sheath tubing and the thermoelements. The sheath tubing is cleaned using a series of timed hydrochloric acid etches, nitric and hydrofloric acid, dilute nitric rinses and multiple distilled water rinse. The material is then cleaned with solvent. All tubes are cleaned internally by hand pumping the etching cleaning fluid through the inside diameters. The thermoelements are abrasively cleanded by introducing the wires into a slurry of alcohol and -600 mesh high purity alumina. The slurry is ultrasonically vibrated. Periodically the wires are removed from the bath and observed under a microscope at 50X. Polishing is completed when surface irregularities in the wires can no loger be observed. The wires are cleaned with solvent. Then, materials are placed in the box through the airlock.

While various assembly steps and weld joints are performed within the glovebox. All work conducted within the box is in an inert atmosphere or in a vacuum. Before and after all weld joints, electrical continuity and insulation resistance of the probe is checked if applicable. All seal welds are leak tested to 3×10^{-8} std. cc/sec.

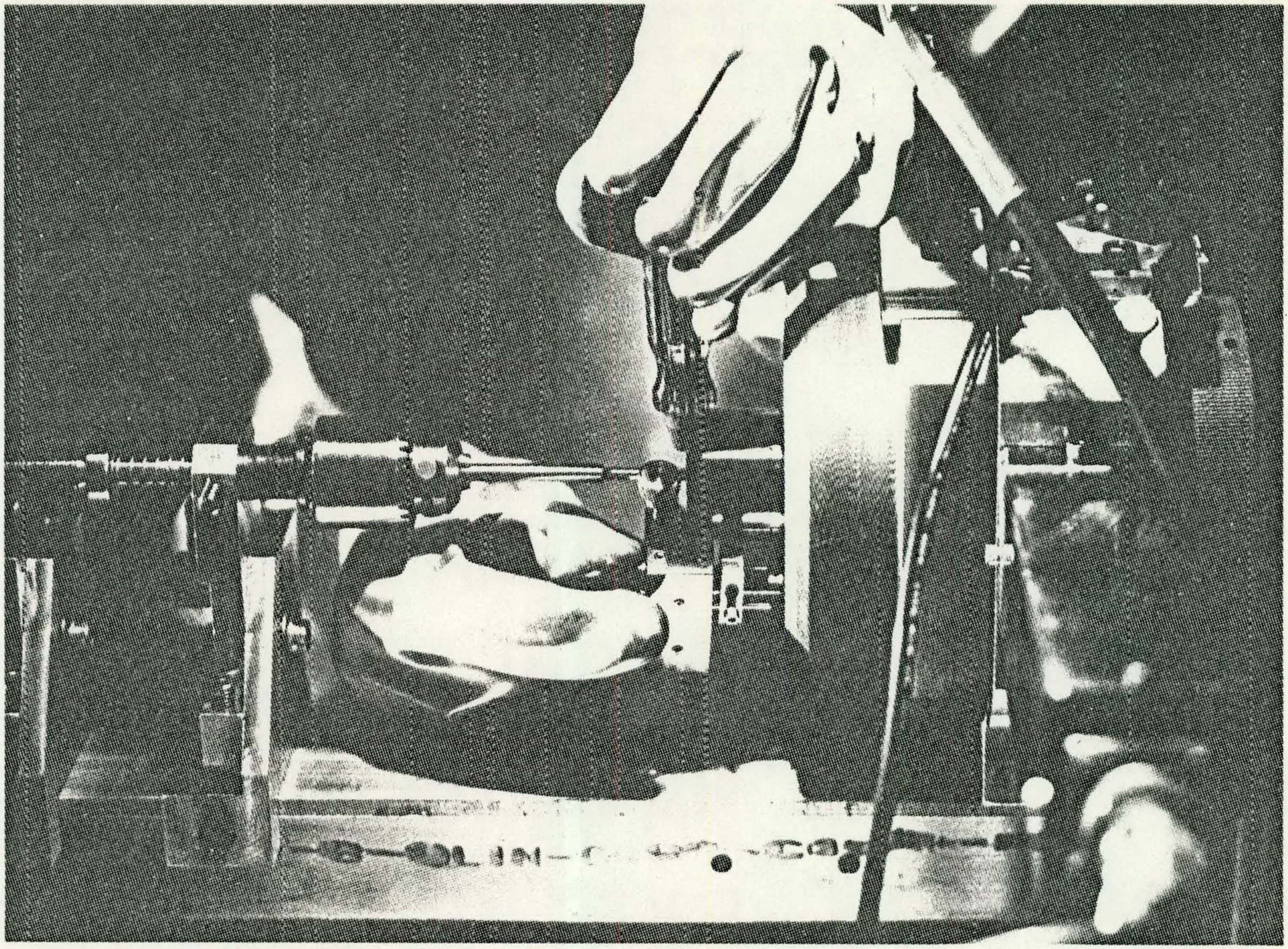

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FIGURE 11. Fixturing for Hermetic Seal-To-Transition Sleeve Weld in Glovebox.

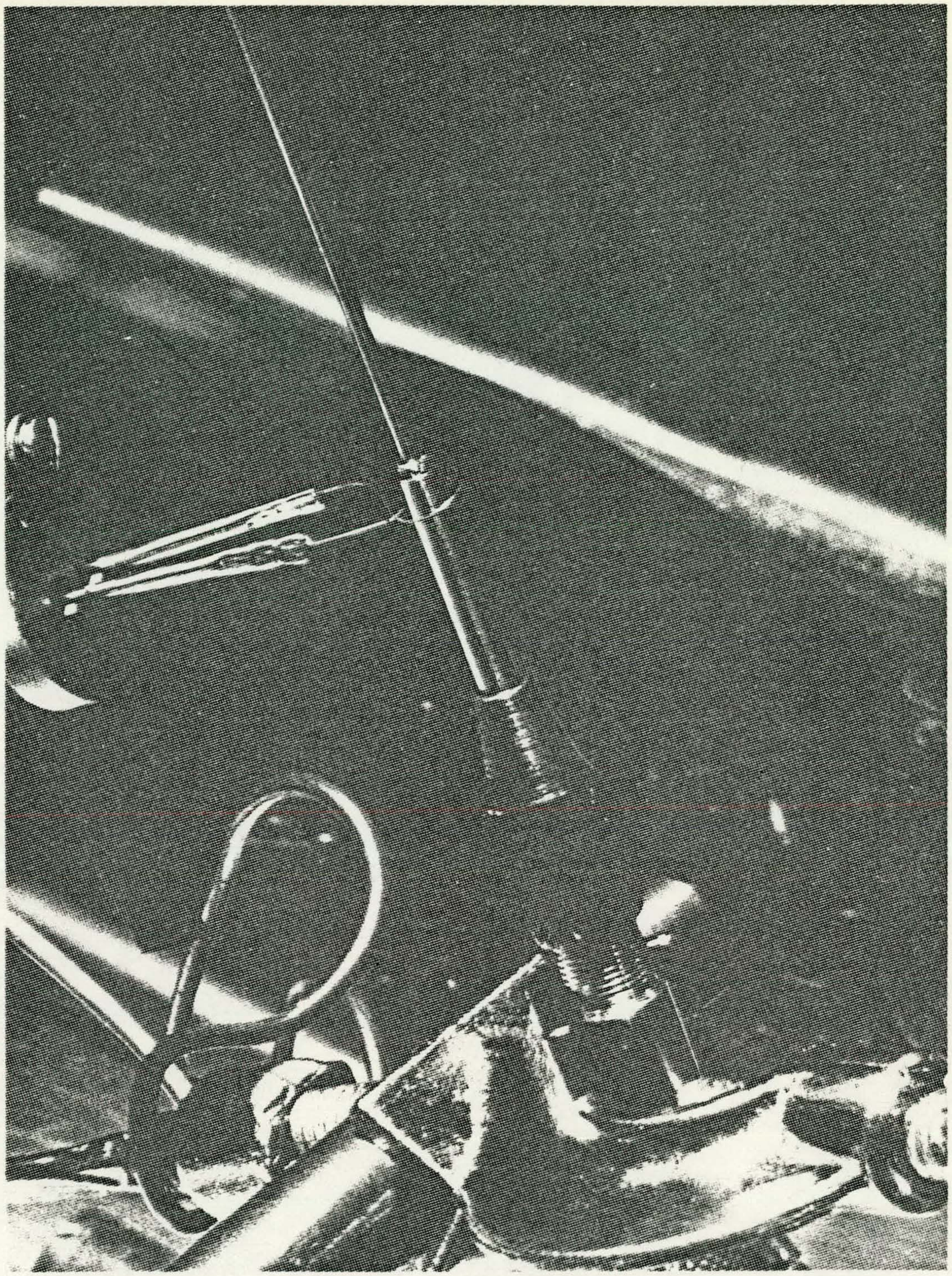

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FIGURE 12. Set-Up For Non-Directional Electron Beam Brazing (Rhenium Tubing to 304 SST with Copper Braze).

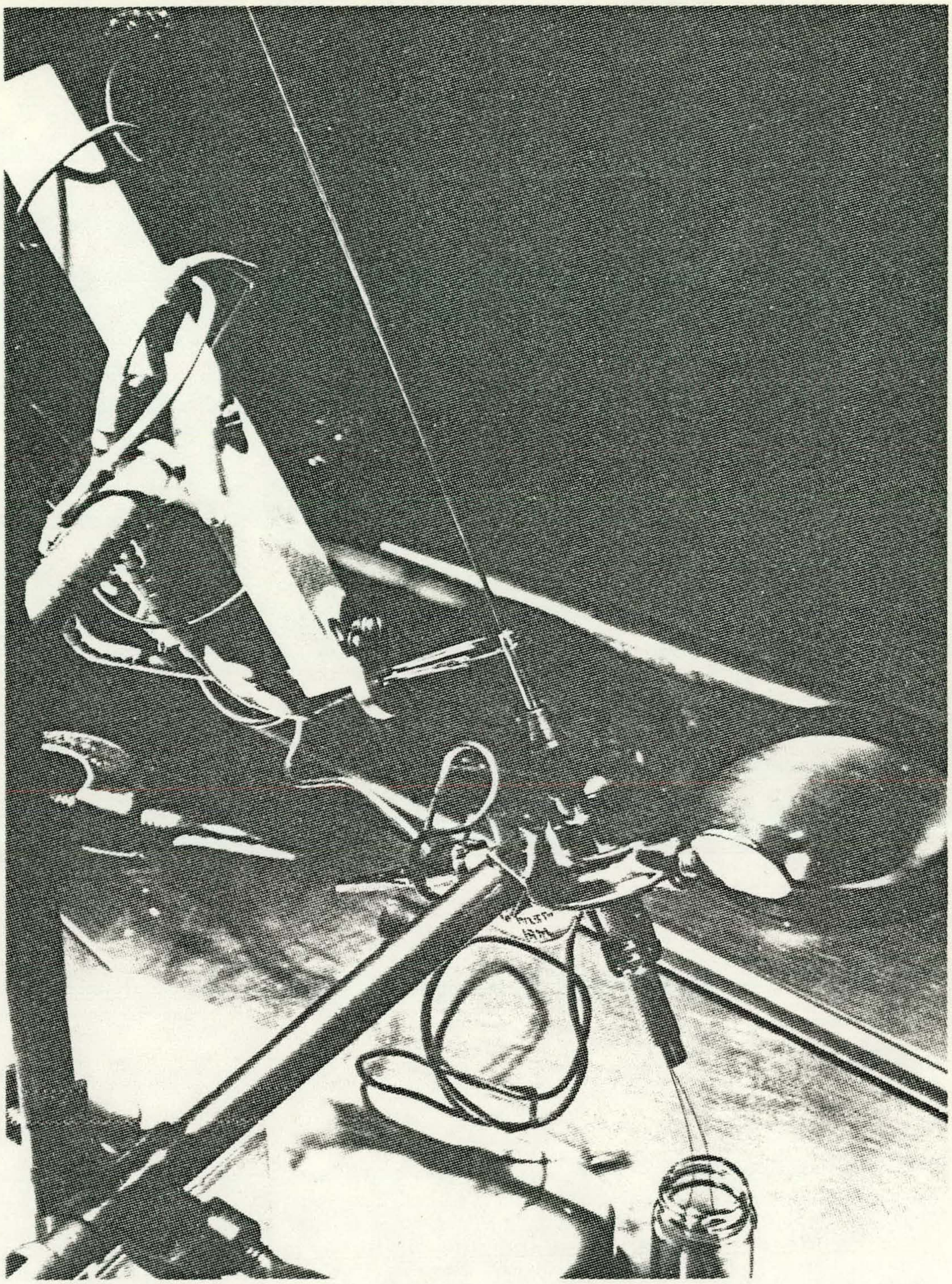

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FIGURE 13. Non-Directional Electron Beam Brazing in Glovebox.

TABLE 6

IN-FUEL THERMOCOUPLE FABRICATION STEPS: PROBE ASSEMBLY

- Etch refractory metal tubing and abrasive clean thermoelements.
- Solvent clean metal parts.
- Vacuum de-gas at 800°K the compensating cable.
- Electron braze sheath tube (refractory metal) to stainless steel transition adapter using copper filler.
- GTAW weld sheath tube shut. Leak test.
- Vacuum de-gas hafnia and alumina insulators at 1900°K.
- String insulators on wire and GTA weld thermocouple junction. Dress down weld bead.
- Insulate junction with single hole hafnia insulator and slip into sheath adapter tube.
- Insulate wires with alumina insulator and install hermetic seal. Perform electrical tests.
- Perform automatic GTA weld of transition adapter to hermetic seal. Leak test welds and electrical test.
- GTAW braze wires to hermetic seal feedthrough tues using copper filler. Leak test brazes and electrical.

Completed probes (Figure 7) are removed from the glovebox for the assembly of the transition junction. The fabrication sequence is outlined in Table 7. The tungsten-rhenium wires and compensating cable leads are laser brazed to 0.635 mm diameter steel tubes. Copper is used as the braze filler material. Split alumina insulators (previously degassed and stored under argon) insulate the two connections and the oversleeve is slipped into place. The ported oversleeve is manually GTA welded to the transition sleeve and the compensating cable assembly. The thermocouple is immediately placed into the glovebox which is then evacuated. The glovebox is backfilled with argon, transition junction is heated with a heat gun, and the glovebox is evacuated. This sequence is repeated three times. Then, the glovebox is backfilled with argon and allowed to purify for one hour. The purge holes in the oversleeve are then GTA seal welded.

The thermocouple assembly is subjected to appropriate electrical and leak tests following all assembly and welding operations. The completed units are x-rayed to precisely locate the thermocouple hot junction.

Fuel pin fission gas plenum and end cap hardware is positioned on the compensating cable. The end cap is precisely positioned on the cable. When the thermocouple is loaded into the fuel pin, the end cap ensures proper location of the hot junction within the fuel column. The end cap is electron beam welded at both ends to the heavy walled cable. Final electrical checks and leak tests are performed and the thermocouple is cleaned.

Thermocouples are loaded into the pins as shown in Figure 6. The end cap is welded to the fuel pin cladding and up to 120 uranium oxide and mixed plutonium-uranium oxide annular fuel pellets are bottom loaded.

All seven W-1 experiment pins with in-fuel thermocouples were successfully fabricated.

TABLE 7

IN-FUEL THERMOCOUPLE FABRICATION STEP:
TRANSITION JUNCTION AND TOTAL ASSEMBLY

- Remove cable from tube furnace and glass.
- Braze cable adapter to cable.
- Remove thermocouple probe from glovebox.
- Laser braze tungsten-rhenium thermoelement to compensating lead in using capillary tubes and copper filler.
- Electrical test.
- Insulate transition junction with degassed split alumina insulators.
- GTA weld transition oversleeve to transition and cable adapters.
- Electrical test.
- Place assembly into glovebox and evacuate and backfill three times with argon.
- GTA weld oversleeve purge holes shut. Leak test and electrical test.
- Remove assembly and x-ray to locate hot (tungsten-rhenium) thermocouple junction.
- Install fuel plenum spacer disk and spring, and locate and position fuel pin upper end cap.
- Electron beam weld end cap to cable in two places. Leak test welds and electrical test.
- Clean and seal in polyethylene for delivery to fuel pin fabrication facility.

4.4 FURNACE TESTING OF IN-FUEL THERMOCOUPLES

Five in-fuel thermocouple probes were tested to establish their calibration in accordance to the experiment engineering test plan. Three Type I and two Type II thermocouple probes were successfully calibrated. All calibrations were in accordance with the current thermocouple calibration standard (IPTS-68). The test results are summarized in Table 8.

Following calibration, the units were life tested at 2573°K (Type I) and 2473°K (Type II). Type II (beryllia) insulated thermocouples failed after 20 and 40 hours. Type I units were tested for 100 hours with a number of cycles before terminating the tests. None of these units failed after this testing.

The compensating cable was calibrated to 1100°K. A plot of the error emf as a function of transition junction temperature when used with the W3%Re versus W25%Re thermoelement pairing is presented in Figure 14.

TABLE 8

IN-FUEL THERMOCOUPLE CALIBRATION TEST RESULTS

Thermocouple	Type	Range	Accuracy/Lifetime
HEDL #05	I	0 - 2873°K	± 2%/100+ hours
HEDL #07	I	0 - 2573°K	± 2%/100+ hours
HEDL #20	I	0 - 2573°K	± 2%/100+ hours
HEDL#102	II	0 - 2673°K	± 2%/20 hours
HEDL #105	II	0 - 2473°K	± 2%/40 hours

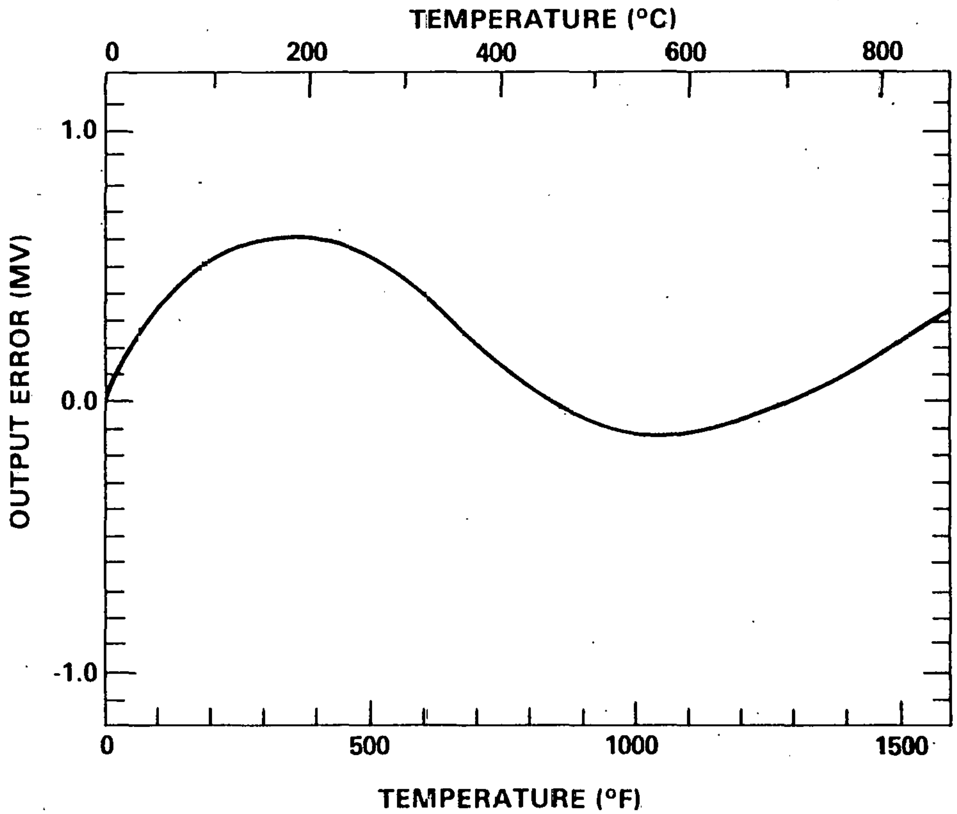

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FIGURE 14. Error at the Transition Junction of W3%Re/W25%Re to 308 Stainless Steel/Alumel Compensating Lead Wires.

Tabulated calibration data and curve fits of the temperature data is presented in Appendix A.

5.0 IN-FUEL THERMOCOUPLE PERFORMANCE IN THE SLSF W-1 EXPERIMENT

Temperatures up to 2866^{o}K were monitored by the four in-fuel thermocouples surviving the initiation of the W-1 SLSF experiment irradiation. Three thermocouples failed prior to the first LOPI indicating an open circuit. All four instruments functioned accurately for the 57 days of testing in ETR (Table 9). The experiment irradiation encompassed five LOPI transients, eight sodium boiling window tests and a steady state fuel conditioning period. Over 550 hours of testing was above 80 percent of full test section power (472 w/cm). The thermocouples were subjected to over 15 heating and cooling transients with maximum heating rates of 150^{o}K per second and maximum cooling rates of 300^{o}K per second.

Figure 15 is a plot of the performance of the thermocouple in pin 3 for the entire test. The thermocouple is located 10.2 cm above the axial mid-plane of the fuel column. Figure 16 is a more detailed plot showing the performance of thermocouples in fuel pins 3, 5, 6, and 7 throughout W-1 irradiation. Test section power is also indicated.

A detail of the final boiling window test is presented in Figure 17. The performance of in-fuel thermocouple 3 and the sodium coolant temperature is presented for the eight seconds of the transient. Figure 18 is a more detailed graph additionally indicating the temperature of thermcouple 5 and the test section sodium flow rate.

The test was successfully terminated following the final boiling window test.

6.0 DEVELOPMENTAL ITEMS

A number of advanced techniques and materials were utilized to fabricate the in-fuel thermocouples. These items are listed in Table 10.

TABLE 9

SLSF W-1 EXPERIMENT IN-FUEL THERMOCOUPLE PERFORMANCE

Thermocouple	Fuel Pin #	Type	Materials (Sheath/Insulator)	Depth from Bottom of Fuel (cm)	Cycles	Max. Temp. (^{o}K)	Time @ 80% Power
TE 22-1	1	I	Re/HfO_2	77.1	0	--	0
TE 22-2	2	I	W-Re/HfO_2	77.1	0	--	0
TE 22-3	3	I	Re/HfO_2	55.9	15	2866	550
TE 22-4	4	II	W-Re/BeO	86.4	0	--	0
TE 22-5	5	II	Mo-Re/BeO	86.4	15	2323	550
TE 22-6	6	I	Re/HfO_2	55.9	15	2850	550
TE 22-7	7	I	Re/HfO_2	55.9	15	2850	550

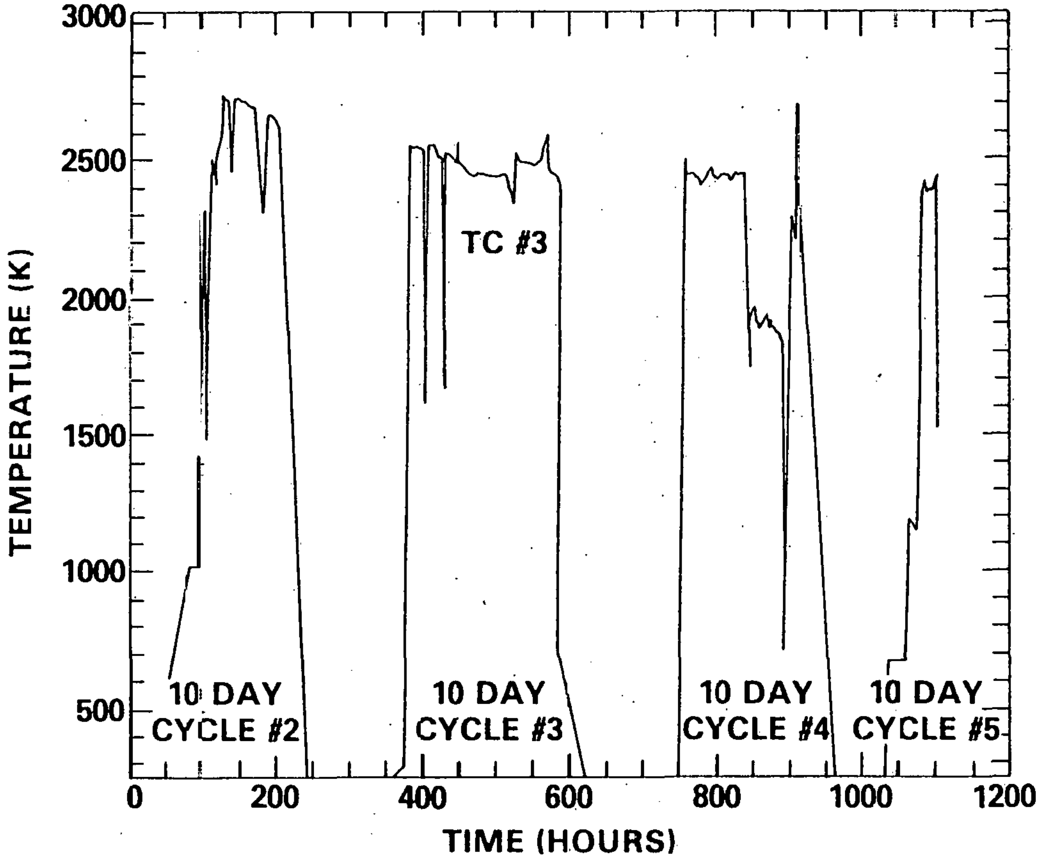

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FIGURE 15. W-1 SLSF Experiment Irradiation History Fuel Centerline Temperatures.

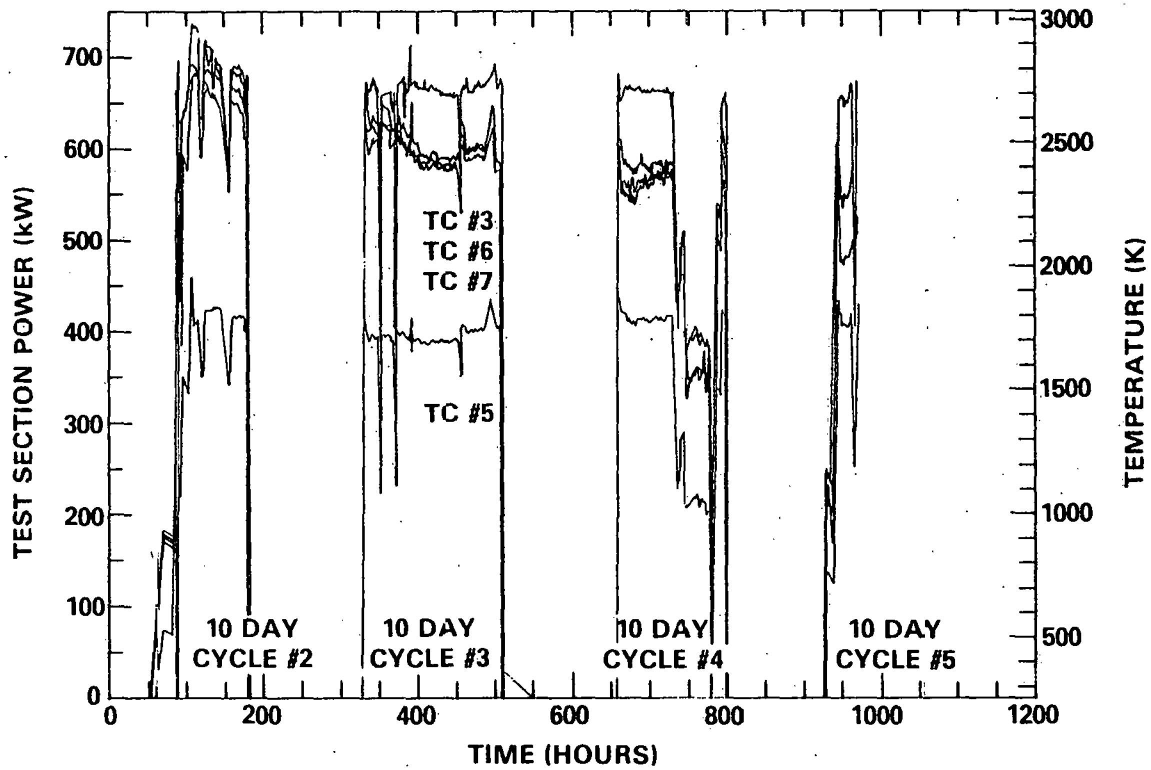

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FIGURE 16. W-1 SLSF Experiment Irradiation History Test Section Power and Fuel Centerline Temperatures.

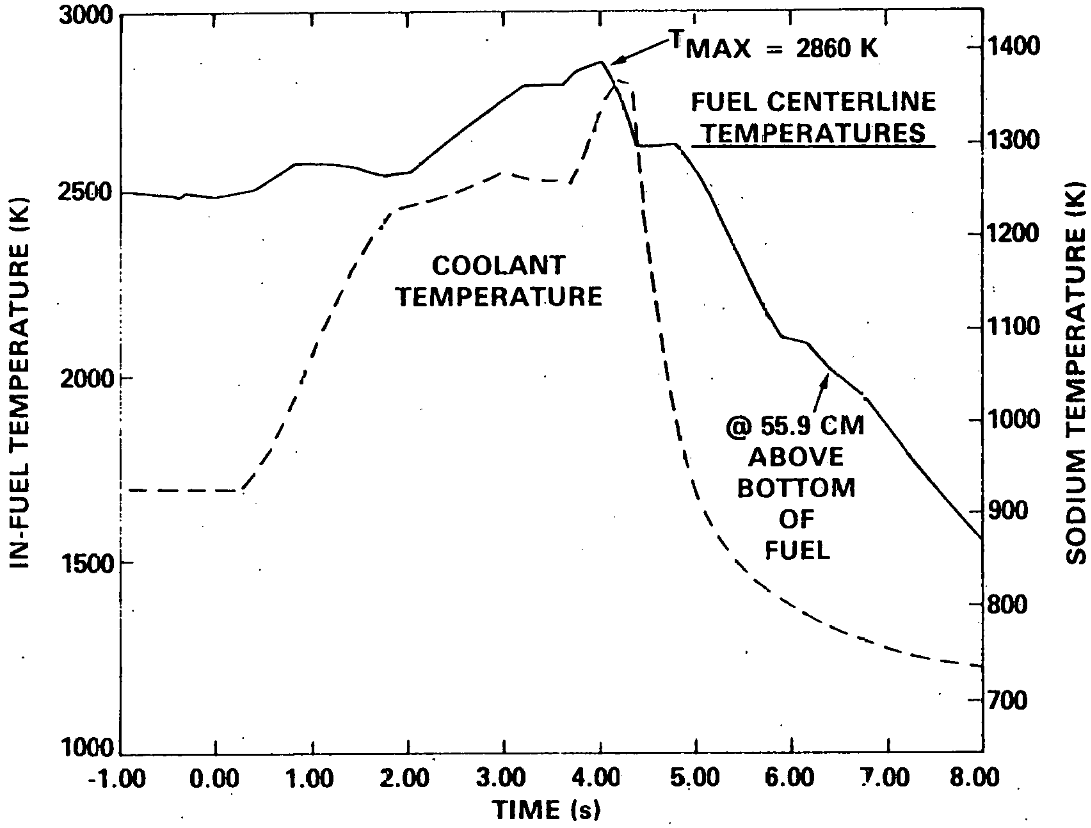

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FIGURE 17. W-1 SLSF Experiment Boiling Window Test #7b'.

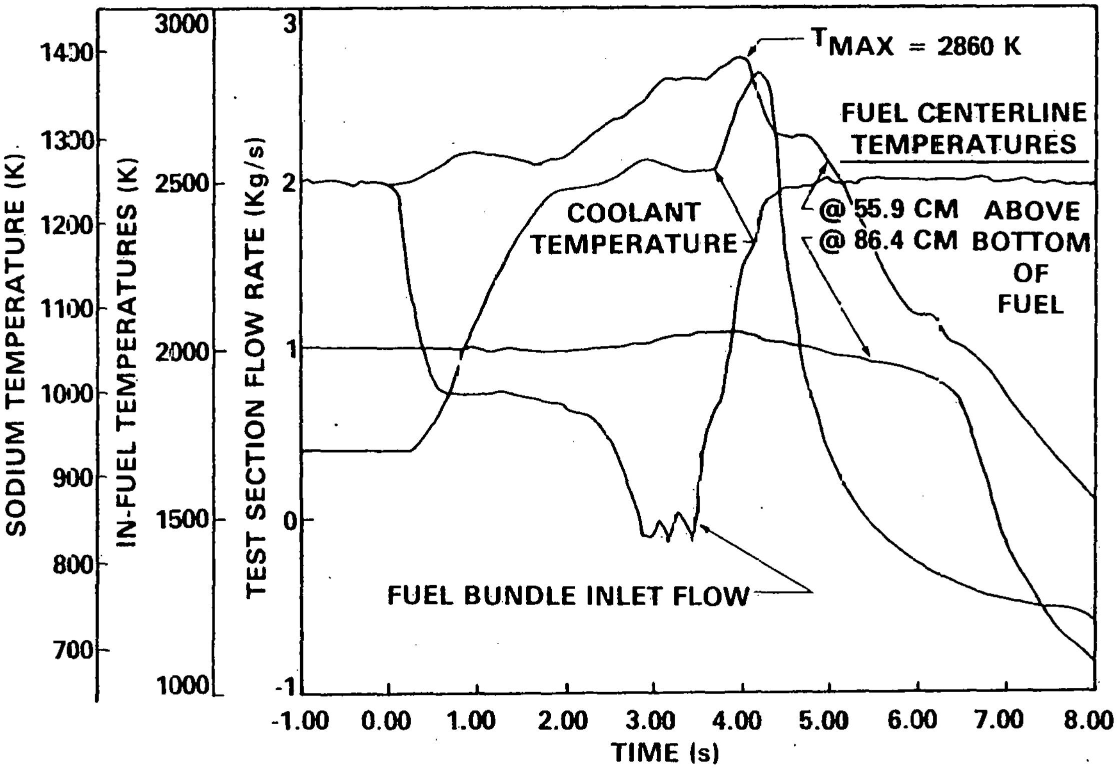

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FIGURE 18. W-1 SLSF Experiment Boiling Window Test #7b'.

TABLE 10

IN-FUEL THERMOCOUPLE FABRICATION: DEVELOPMENT ITEMS

- Total inert atmosphere fabrication and assembly of probes in a vacuum or less than one ppm argon atmosphere.
- Use of electron cloud brazing to join refractory metal sheath tubing to stainless steel adapter.
- Use of automatic GTAW welder to join the 3.42 mm (0.135 inch) diameter hermetic seal to the transition adapter.
- Use of 0.76 m (30 inch) long rhenium tubing and hafnia insulators with the tungsten-rhenium thermoelements.*

* The combination is highly compatible with its own elements and the oxide fuel. The high thermal neutron cross-sections of rhenium and hafnium tend to filter neutrons and protect the tungsten-rhenium thermoelements. This reduces the neutron induced decalibration of the thermocouple.

Advanced designs utilizing the compatible materials and incorporating high reliability, high pressure hermetic seals have been fabricated under HEDL direction for light water reactor safety programs.(7) The fast reactor in-fuel thermocouple has been re-designed to allow for easier assembly, for incorporation of a high temperature, small diameter hermetic seals, and for direct measurement of the transition junction temperature and tungsten-rhenium thermocouple emf.

7.0 CONCLUSIONS

Accurate, long-term measurements of centerline fuel temperatures was achieved using high temperature thermocouples. Successful production of such instruments requires proper, compatible material selection as well as extreme care and cleanliness in fabrication. Both material sources and fabrication techniques and specifications were developed during this and subsequent high temperature thermometry programs at HEDL.

8.0 REFERENCES

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2. W. C. Kuhlman, Research and Evaluation of Materials for Thermocouple Applications Suitable for Temperature Measurement Up to 4500°F on the Surface of Glide Re-Entry Vehicles, ASD-TDR-63-233, March 1963.

3. W. C. Kuhlman, W. G. Baxter, 1000 Hour - 2300 C Thermocouple Stability Tests, GEMP-738, (TID-4500), General Electric Company, Nuclear Systems Program, 1969.

4. W. G. Baxter, R. Pugh, ORTC-III In-Reactor Experiment, GEMP-739, (TID-4500), General Electric Corporation, Nuclear Systems Program, December 1969.

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6. R. B. Fitts, J. L. Miller, E. J. Long, Jr., "Observations on W-Re Thermocouples Use In-Reactor in (U, Pu)O_2 Fuel Pins", Temperature: Its Measurement and Control in Science and Industry, ISA, Pittsburgh, PA, 1974.

7. C. P. Cannon, L. Lunghofer, 2200°C Fuel Centerline Thermocouples for the LOFT Program, HEDL SA-1900, presented at the Nuclear Science/ Nuclear Power System Symposium, San Francisco, October 1979.

APPENDIX A

SLSF W-1 IN-FUEL THERMOCOUPLE CALIBRATIONS AND TRANSITION JUNCTION ERROR CORRECTION

Appendix A

SLSF W-1 IN-FUEL THERMOCOUPLE CALIBRATIONS AND TRANSITION JUNCTION ERROR CORRECTION

The following thermocouples were calibrated for the SLSF W-1 test in-fuel thermocouple calibration data:

HEDL TC #5	273 - 2873^{o}K	Type I
HEDL TC #7	273 - 2573^{o}K	Type I
HEDL TC #20	273 - 2573^{o}K	Type I
HEDL TC #102	273 - 2673^{o}K	Type II
HEDL TC #105	273 - 2473^{o}K	Type II

The compensating extension lead wire cable was calibrated over the temperature range of 273^{o} to 1300^{o}K.

Curve fits of the data from Types I and II thermocouple calibrations were made as a function of both temperature and emf. A tabulation of this data is presented in Tables A-1 and A-2. The curve fit equation coefficients are presented in Table A-3. Data derived from the curve fit relationships agree with vendor bare wire calibrations within 1 percent of full scale. The data for the compensating extension lead wire were also curve fit as a function of temperature and emf. The tabulation of the data is presented in Table A-4. Curve fit equation coefficients are presented in Table A-3.

The emf output must be corrected for various inhomogeneities in the thermocouple circuit. Referring to Figure 1, the emfs generated are summed about the loop. (The potential, $E_i[T]$, is the potential of the given material, i, relative to platinum at a temperature T in ^{o}C.) (Convert from ^{o}K to ^{o}C by subtracting 273.)

$$E_{out} = [E_{Cu}(0^{o}C) - E_{316}(T_1) - E_{308}(T_1)]$$

$$+ [E_{308}(T_2) - E_{W3Re}(T_2)] + [E_{W3Re}(T_H) - E_{W23Re}(T_H)]$$

$$+ \ [E_{W25Re}(T_4) - E_{Al}(T_4)] + [E_{Al}(T5) - E_{316}(T_5)]$$

$$+ \ [E_{316}(0^oC) - E_{Cu}(0^oC)].$$

By definition, the first and last terms are zero. Since $T_2 = T_4$, the following rearranging of the terms is possible:

$$E_{out} = [E_{W3Re}(T_H) - E_{W25Re}(T_H)] - [E_{W3Re}(T_2) - E_{W25Re}(T_2)]$$

$$+ \ [E_{308}(T_2) - E_{AL}(T_2)]$$

$$+ \ [E_{316}(T_1) - E_{308}(T_1)] + [E_{AL}(T_5) - E_{316}(T_5)].$$

The first and second terms are the calibrations of the W3Re/W25Re thermocouples at, respectively, T_H and T_2. The third term is the cable calibration at T_2. The fourth and fifth terms are error signals generated in the connector region. If it is assumed $T_5 = T_1$, the fourth and fifth reduce to the cable calibration at T_1.

Substituting in EMF relationships:

$$E_{out} = EMF_{W-Re}(T_H) - EMF_{W-Re}(T_2) + EMF_{cable}(T_2)$$

$$- \ EMF_{cable}(T_1).$$

Rearranging:

$$EMF_{W-Re}(T_H) = E_{out} + EMF_{W-Re}(T_2) - EMF_{cable}(T_2)$$

$$+ \ EMF_{cable}(T_1).$$

The first term, E_{out}, is measured at the compensating cable end. The second and third terms are obtained by measuring T_2 (the transition temperature), and calculating the appropriate EMF from either equation 2, 4, or 6 in

Table A-3, or using Tables A-1, A-2, or A-4. The fourth term is obtained from either equation 6, Table A-3, or Table A-4 for a temperature T_1.

The true junction temperature, T_H, is then obtained by substituting the corrected emf, $EMF_{W-Re}(T_H)$, into either equation 1 or 3 in Table A-3.

TABLE A-1

SLSF W-1 IN-FUEL THERMOCOUPLE CALIBRATION
FOR HEDL FABRICATED (TYPE I) PROBES

Temperature (^{o}C)	EMF (Mv)	Temperature (^{o}C)	EMF (Mv)
0	0.0	1100	20.358
50	0.537	1200	22.361
100	1.204	1300	24.309
150	1.924	1400	26.194
200	2.692	1500	28.006
250	3.503	1600	29.736
300	4.354	1700	31.387
350	5.239	1800	32.945
400	6.154	1900	34.413
450	7.097	2000	35.788
500	8.063	2100	37.071
550	9.049	2200	38.264
600	10.052	2300	39.368
700	12.093	2400	40.387
800	14.165	2500	41.325
900	16.245	2600	42.186
1000	18.315	2700	42.977

* The above data are derived from the polynomial curvefit, equation 1, in Table A-3.

** Cold junction reference temperature = $0^{o}C$ ($273^{o}K$).

*** Thermoelement wires are W3Re (Hoskins Lot #314) and W25Re (Hoskins Lot #26232).

**** To convert to absolute temperature (^{o}K), add 273 to the temperature listed.

TABLE A-2

SLSF W-1 IN-FUEL THERMOCOUPLE CALIBRATION
FOR HEDL/VENDOR FABRICATED (TYPE II) PROBES

Temperature (°C)	EMF (Mv)	Temperature (°C)	EMF (Mv)
0	0.0	1100	20.177
50	0.594	1200	22.148
100	1.254	1300	24.071
150	1.969	1400	25.936
200	2.731	1500	27.736
250	3.537	1600	29.466
300	4.382	1700	31.122
350	5.260	1800	32.700
400	6.169	1900	34.198
450	7.103	2000	35.614
500	8.060	2100	36.946
550	9.036	2200	38.194
600	10.026	2300	39.356
700	12.042	2400	40.431
800	14.083	2500	41.416
900	16.130	2600	42.310
1000	18.167	2700	43.109

* The above data are derived from the polynomial curvefit, equation 3, in Table A-3.

** Cold junction reference temperature = 0°C (273°K).

*** Thermoelement wires are W3Re (Engelhard Lot #021) and W25Re (Engelhard Lot #017).

**** To convert to absolute temperature (°K), add 273 to the temperature listed.

TABLE A-3

CURVEFIT COEFFICIENTS FOR SLSF W-1 IN-FUEL THERMOCOUPLE TEMPERATURE/EMF RELATIONSHIPS

General Equation Form: $Y = f(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5$

Equation	Relationship	X	Y	Range of X	a_0	a_1	a_2	a_3	a_4	a_5
1	Type I TC T = f(EMF)	Mv	^oC	0 - 45 Mv	4.17956	8.2156×10^{1}	-3.845276	2.0079997×10^{-1}	-4.94414×10^{-3}	4.9112859×10^{-5}
2	Type I TC EMF = f(T)	^oC	Mv	0 - 2600^oC	-7.82837×10^{-2}	1.1586551×10^{-2}	$+1.2528 \times 10^{-5}$	$-6.9414133 \times 10^{-9}$	$1.2972424 \times 10^{-12}$	$-8.276553 \times 10^{-17}$
3	Type II TC T = f(EMF)	Mv	^oC	0 - 45 Mv	3.41105	8.40564×10^{1}	-4.16444	2.2381×10^{-1}	-5.5600×10^{-3}	$5.44269787 \times 10^{-5}$
4	Type II TC EMF = f(T)	^oC	Mv	0 - 2600^oC	-7.64×10^{-2}	1.1409694×10^{-2}	1.291463×10^{-5}	-7.788856×10^{-9}	$1.8117556 \times 10^{-12}$	-1.72973×10^{-16}
5	Compensating Extension Lead Wire T = f(EMF)	Mv	^oC	0 - 22 Mv	-0.95984	6.44639×10^{1}	8.2025526×10^{-1}	-1.997343×10^{-1}	8.920339	1.3429078×10^{-4}
6	Compensating Lead Wire EMF = f(T)	^oC	Mv	0 - 1100^oC	-1.220731×10^{-2}	1.6213995×10^{-2}	$-6.7057268 \times 10^{-6}$	$1.69012347 \times 10^{-8}$	$-8.5940134 \times 10^{-12}$	$1.7466759 \times 10^{-15}$

* To use curve 1, 3, and 5 in an absolute temperature scale (^oK), add 273 to the Y value.

** To use curves 2, 4, and 6 in an absolute temperature scale (^oK), subtract 273 from the temperature to convert to ^oC prior to using the curve fit equation.

TABLE A-4

SLSF W-1 IN-FUEL THERMOCOUPLE CALIBRATION
FOR COMPENSATING EXTENSION LEAD CABLE

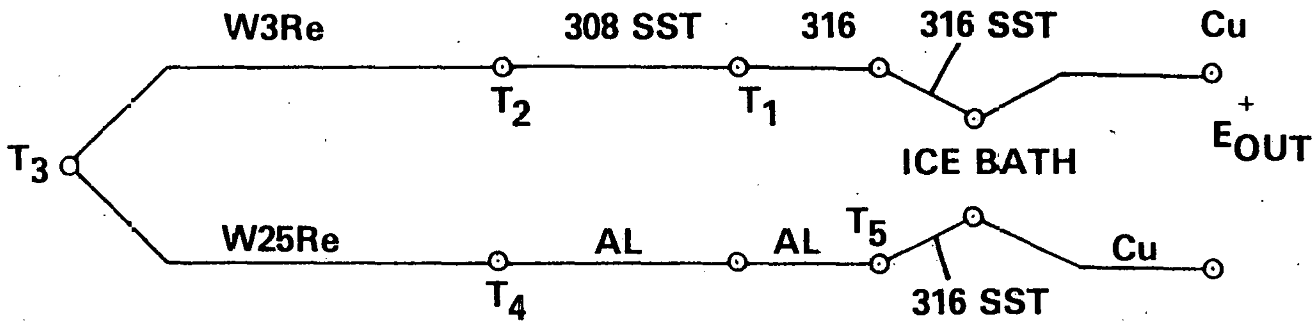
Temperature (°C)	EMF (Mv)	Temperature (°C)	EMF (Mv)
0	0.0	550	8.989
50	0.784	600	9.972
100	1.558	650	11.000
150	2.322	700	12.074
200	3.084	750	13.195
250	3.854	800	14.363
300	4.639	850	15.580
350	5.446	900	16.845
400	6.280	950	18.158
450	7.146	1000	19.520
500	8.048	1050	20.930

* The above data are derived from the polynomial curvefit, equation 5, in Table A-3.

** Cold junction reference temperature = 0°C (273°K).

*** Compensating extension lead wires are 308 SST and Alumel (P.O. #Y2D-444-10735).

**** To convert to absolute temperature (°K), add 273 to the temperature listed.



1 - TOP OF HERMETIC SEAL
2 - TRANSITION JUNCTION, FISSION GAS PLENUM
3 - HOT JUNCTION, IN-FUEL
4 - TRANSITION JUNCTION, FISSION GAS PLENUM
5 - TOP OF VIKING CONNECTOR
AL - ALUMEL

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FIGURE A-1. Schematic of In-Fuel Thermocouple System.